

I hereby certify that this paper is being deposited with the United States Postal Service as Express Mail in an envelope addressed to: Box Patent Application, Asst. Comm. for Patents, Washington, D.C. 20231, on this date.

Dec. 13, 2001
Date

Andy B. R.
Express Mail Label No.: EL846222354US

1 UNITARY METAL STRUCTURAL MEMBER WITH INTERNAL
2 REINFORCEMENT

3
4
5 CLAIM FOR PRIORITY

6 This application claims the benefit of U.S. Provisional Application
7 No. 60/255,242, filed December 13, 2000, under 35 U.S.C. §119.

8
9 FIELD OF THE INVENTION

10 The present invention relates generally to structural members.

11 BACKGROUND OF THE INVENTION

12 Metal structural members have a wide-ranging applicability as
13 components in various types of structural frames. The members may be used, for
14 example, in aircrafts and automobiles to form a structural frame. The members
15 might also find applicability in building construction and consumer devices.
16 Another potential application is in spacecraft. The members are typically
17 elongated components. A critical property for structural members is strength to
18 weight ratio. Weight is an obvious drawback in many applications, just as
19 strength is an obvious advantage.

20 Conventional structural metal members are composed of rolled or
21 extruded components with constant cross-sectional size and shape, and a constant
22 wall thickness. Typically, the cross-section of a member is circular so that the
23 overall shape of the support member is cylindrical. However, the member may

1 have a rectilinear cross-section. Generally, the strength to weight ratio in these
2 types of members is a function of the material and the wall thickness, which might
3 be thick enough to form a substantially solid member in some instances or a
4 substantially hollow member in other instances.

5 Selection or design of a particular component with a specific wall
6 thickness and cross-sectional geometry is determined by the maximum loads and
7 stresses a particular portion or portions of that member will be required to transfer
8 or absorb in specified service conditions. Put another way, the cross-sectional size
9 and wall thickness of the entire length of the structural member is dictated by the
10 point or points of maximum stress (plus an added safety factor), and the
11 component is oversized (i.e., contains excess material and strength) elsewhere
12 along its straight or curvilinear length. Increased wall thickness of a hollow
13 support member increases the strength of the member (up to an internally solid
14 structure), but with a resultant increase in the materials needed to produce the
15 member, and the overall weight of the member. Likewise, the cross-sectional size
16 can be increased with a resultant increase in materials.

17 18 SUMMARY OF THE INVENTION

19 The present invention provides a metal unitary member with a
20 number of features having parameters that can be varied alone or in combination
21 with other parameters to customize configuration of the members for a particular
22 service environment. A unitary structural member of the invention includes a

1 plurality of web portions extending radially from each other and extending with
2 each other in an axial direction. A plurality of outer portions extend in an axial
3 direction with the web portions and extend between the web portions in cross-
4 section. The plurality of outer portions define a radially outer surface of the
5 member. The axial directions of the web portions and outer portions may be
6 straight or curvilinear so that the web portions and outer portions may be straight
7 or curvilinear in trajectory.

8 ~~Preferably, the plurality of web portions extend radially from a~~
9 ~~substantially central portion that extends in an axial direction with the web~~
10 ~~portions and the outer portions. The axial direction of the substantially central~~
11 ~~portion may be straight or curvilinear. The central portion, the plurality of web~~
12 ~~portions and/or the radially outer portions of the unitary tubular member may have~~
13 ~~a linear or curvilinear trajectory in a radial direction.~~

14 Preferably, the plurality of web portions includes a plurality of
15 perforations. The plurality of web portions may vary in radial length at various
16 axial positions along the member. The outer portions spanning between the web
17 portions may expand in arc length, and as a result, the unitary tubular member may
18 vary in cross-sectional size and/or shape. The outer portions preferably are
19 arched, but may instead be otherwise curvilinear or linear in configuration to form
20 complex and variable shapes and/or variable sizes of the cross-section of the
21 member. The web portions may be disposed at substantially equal intervals,
22 disposed with varying intervals but symmetrically, or disposed at varying intervals

1 to produce an asymmetrical cross-section. By varying the shape and/or length of
2 the outer portions and the number, configuration, or positioning of the web
3 portions, a variety of cross-sectional shapes and sizes can be designed and
4 optimized for particular service conditions.

6 BRIEF DESCRIPTION OF THE DRAWINGS

7 FIG. 1 is an enlarged end view of a unitary structural member according to
8 one embodiment of the present invention;

9 FIG. 2 is a perspective view of a pair of connected unitary structural
10 members;

11 FIG. 3 is a cut away view of a unitary structural member according to
12 another embodiment of the present invention;

13 FIGS. 4A-4D are simplified drawings of unitary structural members varying
14 in web portion radial length and/or trajectory;

15 FIGS. 5A-5D are simplified drawings of embodiments of the unitary
16 structural member having varying numbers and configurations of web portions;

17 FIGS. 6A-6D are simplified sketches of unitary structural members having
18 varying numbers and/or shapes of web portions and/or outer portions;

19 FIG. 7 is a perspective view of a pair of unitary structural members
20 showing connecting structures;

21 FIG. 8 is an analytical taxonomy of preferred types of processes for
22 manufacturing complex shaped metal components;

1 FIG. 9 illustrates computer-aided manufacturing processes, including some
2 for forming unitary structural members of the invention;

3 FIG. 10 is a chart showing steps in an investment casting process for
4 forming a unitary structural member of the invention;

5 FIG. 11 is a chart summarizing steps in an investment casting process for
6 manufacturing a prototype unitary structural member;

7 FIG. 12 is a screen capture of computer models of pattern components for
8 an example embodiment of a unitary structural member;

9 FIG. 13 is a screen capture showing the internal structure of the unitary
10 structural member;

11 FIG. 14 shows, in solid and in line drawing, a digital assembly of a pair of
12 unitary structural members;

13 FIG. 15 shows examples of three-dimensional printing of expendable
14 patterns for manufacturing the unitary structural member;

15 FIG. 16 shows a pair of pattern components in a "green" state after powder
16 removal;

17 FIG. 17 shows part patterns for producing a unitary structural member, with
18 gating attached;

19 FIG. 18 shows a step in an investment casting process for producing unitary
20 structural member;

21 FIG. 19 shows steps in the investment process following the steps shown in
22 FIG. 18;

1 FIG. 20 shows molds for forming a unitary structural member, drying in
2 air;

3 FIG. 21 shows a metal pouring operation;

4 FIG. 22 shows solidifying castings in which the metal has been poured;

5 FIG. 23 shows steps in destruction of the ceramic mold shown in FIG. 22;

6 FIG. 24 shows the unitary structural member in its "as cast" state prior to
7 removal of gating;

8 FIG. 25 shows castings for the unitary structural member after removal of
9 the portion of the gate;

10 FIG. 26 shows the casting of FIG. 25 after removal of the remainder of the
11 gating;

12 FIG. 27 shows a grinding process for the casting of FIG. 26;

13 FIG. 28 shows steps in welding together a pair of unitary structural
14 members;

15 FIG. 29 shows the welded pair of unitary structural members after the
16 process shown in FIG. 28;

17 FIG. 30 shows the joined unitary structural members of FIG. 29 during a
18 sandblasting process;

19 FIGs. 31A and 31B show radiographs of the formed unitary structural
20 member; and

21 FIG. 32 is a diagram showing the process for indirect additive manufacture
22 of a unitary structural member.

1
2 DETAILED DESCRIPTION OF THE INVENTION
3

4 A metal unitary structural member of the invention includes a
5 plurality of web portions extending radially from one another and extending with
6 each other in an axial direction, and a plurality of outer portions extending
7 between the web portions in cross-section. A high strength to weight ratio is
8 achieved, especially with the use of preferred perforations in the web.
9 Advantageously, the general invention admits of variations for one or more of the
10 portions of the unitary tubular member, e.g., the trajectory of the web portions or
11 outer portions, or the variation of the radial length of the web portions along the
12 axial length. These and other variations of the general invention permit a designer
13 to customize various features of the unitary member for particular uses or
14 operating environments, such as for specific aspects of their intended service
15 conditions, with a greater flexibility in customization than many conventional
16 designs. In addition, designers are freed from basing a complete design of a
17 structural member on its point of maximum stress.

18 Referring now to the drawings, FIG. 1 shows a first, preferred type
19 of embodiment unitary metal structural member 10 according to the present
20 invention, and illustrates a number of preferred features. To provide reinforcing
21 support (stiffness or strength, for example) to the unitary structural member 10,
22 and to increase the strength-to-weight ratio of the member, a plurality of web
23 portions 12 are provided, which extend with each other in an axial direction, and

extend radially from each other. The axial direction of the web portions 12 may be linear or curvilinear in trajectory. The web portions 12 may be linear in radial trajectory (as shown in FIG. 1) or curvilinear, as shown by example in FIG. 2 and extend between outer portions 14. Radial, as used herein, indicates a trajectory, whether linear or curvilinear, that originates at the intersection of web portions at any point along an axial extension thereof and extends to an outer portion 14 at any point along an axial extension thereof. In segments, the web portions 12 form an internal reinforcement structure for the unitary structural member 10. The number and radial length and/or shape of included web portions 12 may vary according to, for example, the size and intended service conditions of the particular unitary structural member 10. Preferably, though, the unitary structural member 10 includes at least three web portions 12 for distributing a load applied to the member.

Extending between the plurality of web portions 12 in cross-section, a plurality of outer portions 14 extend around the unitary structural member 10 and in an axial direction with the web portions 12, to define in combination an outer surface 16 of the unitary structural member. The outer surface 16 may be of a complex cross-sectional shape, such as the shape formed by the arched outer portions 14 shown in FIG. 1, or may be, for example, circular or rectilinear in cross-section. The preferred arched configuration for the outer portions 14 further enhances structural integrity of the unitary structural member 10. Loads applied to outer portions of the arched outer portions 14 (lateral loads) in the embodiment

1 shown in FIG. 1 are efficiently directed to and through one or more of plurality of
2 web portions 12. This preferred type of the unitary structured member 10
3 improves stiffness of the internal reinforcement for the unitary structural member
4 and facilitates optimal distribution of lateral loads to the internal plurality of web
5 portions 12.

6 As shown in FIG. 1, and as more clearly seen in FIG. 2, for example,
7 the outer surface defined by the arched outer portions may form a corrugated
8 configuration, with furrows 18 that align with the plurality of web portions. The
9 extent of the corrugation (furrow 18 depth) may be customized depending upon
10 component-specific service conditions by varying the radial length of selected web
11 portions 12 and the shape and/or thickness of selected radially outer portions.

12 In the embodiment shown in FIGs.1 and 2, the web portions 12
13 extend from one another and from a substantially central (in cross-section) portion
14 20 at or near the intersection of the web portions 12. The central portion 20 itself
15 extends axially along the member 10. The central portion 20 may, but not
16 necessarily, be continuous along its axial direction. The axial direction defined by
17 the central portion 10, preferably followed substantially in parallel by the
18 remainder of the unitary structural member 10, including the web portions 12 and
19 the outer portions 14, may be either lineal or curvilinear in trajectory. FIG. 2, for
20 example, shows the member, including the central portion 20, extending axially
21 along a curvilinear trajectory. The central portion 20 shown in FIG. 1 is
22 substantially circular in cross-section, but in other embodiments, it may have a

1 different cross-sectional shape. One skilled in the art will appreciate that, by
2 selectively varying the axial trajectory of the central portion 20, web portions 12
3 and/or the outer portions 14, the overall trajectory of the unitary structural member
4 10 can be configured to meet particular structural needs. In the radial direction,
5 the central portion 20 may be symmetrical, or asymmetrical, such as in a spline
6 trajectory.

sub
A3

FIG. 10

7 The (optional) central portion 20, the plurality of web portions 12,
8 and the outer portions 14 are preferably integral portions of the unitary structural
9 member 10. By "unitary", it is intended to mean that the unitary structural
10 member 10 is formed in a single, integral piece; that is, the unitary structural
11 member is not a fabrication of separate sections. However, individual unitary
12 structural members 10 can themselves be sections of a larger combined structure
13 22, as shown in FIG. 2. In the arrangement shown in FIG. 2, a pair of unitary
14 structural members 10 having a configuration similar to that shown in FIG. 1, are
15 connected via mating connective structures 24, one of which is more clearly seen
16 in FIG. 7. The connective structures 24 may be integrally formed on one or both
17 ends of the unitary structural members 10. Preferably, the connective structures
18 24 include a self-registering connector 10; that is a connector 26 configured to
19 prevent relative rotation of connected members. The self-registering connector 26
20 may include a male or female connector 28, as shown in FIG. __, a pin or other
21 independent connection, or another type of connection. To combine a pair of the

1 unitary structural members 10, the connective structures 24 are connected and
2 preferably adhered, welded or bonded to form the combined structure 22.

3 As further shown in FIG. 1, a plurality of perforations 30 is formed
4 within the plurality of web portions 12 to form perforated web portions. The
5 perforations 30 are disposed and arranged to be axially aligned with the plurality
6 of web portions 12. Though the perforations 30 are not required, the present
7 inventor has discovered that perforated web portions 12 provide significant
8 structural integrity with a high strength-to-weight ratio. The perforations 30 also
9 provide additional ways to customize the unitary structural member 10 by varying,
10 for example, the configuration and arrangement of the perforations.

11 As shown in FIG. 1, the perforations 30 may be relatively large and
12 centrally located on the plurality of web portions 12, and may be disposed within
13 the plurality of web portions radially symmetrically with respect to the central
14 portion 20. The perforations 30 may also be radially disposed about an
15 intersection of the web portions 12, as shown in FIG. 3. In this way, the
16 perforated web portions 12 are conceptually similar to internal surface ribs that
17 intermittently bridge to their opposing counterparts via the center of a particular
18 cross-section. If such perforations 30 are part of web portions 12 that extend from
19 the central portion 20, the perforations create discontinuity of the central portion at
20 their location. The perforations 30 preferably are axially disposed within the
21 plurality of web portions 12 along their respective axes. In this way, it will be
22 appreciated that, as is apparent in FIG. 1, cross-sections of the unitary structural

1 member 10 will vary at least in shape along particular axial positions along the
2 unitary structural member. For at least this reason, it is also to be understood that,
3 by describing that the plurality of web portions 12 "axially extend" along the
4 unitary structural member 10, the cross-sections may vary in shape and/or size
5 along the various axial portions of the unitary structural member, though the
6 member may otherwise be of substantially uniform cross-sectional size and shape.

7 The external surfaces 16, whether corrugated, smooth, or otherwise,
8 may also include perforations (not shown) in order to further optimize strength-to-
9 weight ratios. The use of external perforations may also be dependent on
10 anticipated service conditions. Alternatively, the outer surface 16 may be
11 relatively continuous and/or smooth in profile.

12 The wall thickness of the central portion 20, plurality of web
13 portions 12, and/or the plurality of outer portions 14 may be either constant or
14 variable depending on, for example, manufacturing process requirements and the
15 extent to which the strength-to-weight ratio is optimized. For example, to provide
16 a relatively smooth, cylindrical outer surface 16 with the arched outer portions 14,
17 as shown in FIG. 5D, a designer may selectively increase the wall thickness of the
18 outer portions to fill in the furrows 18.

19 It is an important aspect of the present invention that, among other
20 things, the cross-sectional size and/or shape, wall thickness, axial trajectory,
21 component material, and/or arrangement of the unitary structural member 10,
22 including the perforations 30, can substantially vary as a result of varying the

1 radial size or shape or the trajectory of the central portion 20, plurality of web
2 portions 12, or plurality of outer portions 14, or selected ones of these portions,
3 throughout the member, or at axial positions along the member. The variances
4 contemplated may be present between particular unitary structural members 10, or
5 within one of the unitary structural members. By selectively varying one or more
6 of these parameters in the design of the member 10, unique unitary structural
7 members 10 may be formed that are optimized for specific use environments. The
8 unitary structural members may vary in, for example, cross-sectional size or shape,
9 trajectory shape, or number of web portions 12.

10 By varying size and/or shape of one or more of the plurality of web
11 portions 12, the cross-sectional size and shape of the unitary structural member 10
12 varies accordingly. The unitary structural members 10 may thus be designed to
13 have optimum sizes, cross-sectional shapes, or strengths at particular axial
14 positions to meet particular service conditions. For example, variable service
15 requirements along the unitary structural member 10 length may result in
16 optimizations in terms of size, shape, strength, and/or material usage.

17 FIGs. 4A-6D are illustrative examples of embodiments of the unitary
18 structural member 10, showing effects of varying one or more of the above-
19 described parameters on embodiments of the unitary structural member. FIGs.
20 4A-4D illustrate the effect of variations in the radial length of the plurality of web
21 portions 12 and/or the trajectory of the central portion 20 (and thus the unitary
22 structural member 10). In FIG. 4A, the radial length of the plurality of web

1 portions 12 varies along axial positions of the unitary structural member 10,
2 increasing near the axial middle of the member, and decreasing near the ends. The
3 plurality of outer portions 14 vary in arc length accordingly to extend between the
4 plurality of web portions 12, so that the unitary structural member 10 maintains a
5 cross-sectional shape that is substantially similar in proportion. The axial location
6 of maximum cross-sectional size may be designated to meet particular service
7 conditions. The axial trajectory of the unitary structural member 10 in FIG. 4A is
8 curvilinear.

9 By keeping the radial length of the plurality of web portions 12
10 relatively constant while maintaining the curvilinear trajectory of the central
11 portion 20, the unitary structural member 10 shown in FIG. 4B can be produced.
12 FIGs. 4C and 4D show the effect of altering the design of FIGs. 4A and 4B,
13 respectively, by providing a straight trajectory for the central portion 20.

14 ~~FIGs. 5A-5D illustrate an effect of varying the number of web~~
15 ~~portions 12, where the plurality of web portions and the arched outer portions are~~
16 ~~disposed about the central portion 20 in generally equal intervals. FIGs. 5A, 5B,~~
17 ~~and 5C include three, four, and five web portions 12, respectively. The arched~~
18 ~~outer portions span between the plurality of web portions 12, forming corrugations~~
19 ~~in the outer surface 16 of the unitary structural members 10. It will be apparent~~
20 ~~that as the number of symmetrical web portions 12 increases, the outer surface 16~~
21 ~~may become more circular in cross-section. FIG. 4D includes eight web portions~~
22 ~~12, and the wall thickness of the web portions 14 and/or the arched outer portions~~

1 are increased at the circumferential position of the radially outer portions. This
2 design, as described above, may result in a smooth, continuous outer surface 16, as
3 shown.

4 FIGS. 6A-6D illustrate an effect of varying the number, length,
5 and/or direction of the plurality of web portions 12, and also varying the shape of
6 the radially outer portions 14 spanning the web portions. FIG. 6A shows six web
7 portions 12 that are disposed unequally about the cross-sectional profile of the
8 unitary structural member 10. The arched outer portions 14 span to connect the
9 web portions 12. In FIG. 6B, seven web portions 12 are shown, and the radially
10 outer portions 14 vary. Some outer portions 14 are arched, and have a greater wall
11 thickness at the web portions 12 to provide a smooth outer surface 16. Other outer
12 portions 14, however, are not arched, but are straight, providing a rectilinear side
13 to the unitary structural member 10. The web portion 12 extends beyond the outer
14 portion 14 disposed over it to create a T-shape profile 32 at the top (as shown) of
15 the unitary structural member 10. FIGS. 6C and 6D show variations of the unitary
16 structural member 10 of FIG. 6B, having five and three cavities, respectively,
17 without a web portion 12 extending beyond the outer portions 14.

18 FIG. 3 additionally illustrates one example of the central portion 20
19 being generally curvilinear in cross-section, as opposed to a substantially
20 cylindrical central portion 20 shown in other embodiments.

21 The perforations 30 within the plurality of web portions 12 may be
22 disposed symmetrically about the central portion 20, as shown in FIG. 1, or

1 additionally or alternatively may be centered on the plurality of web portions 12 as
2 shown in FIG. 3, and as described above. In either approach, the size and quantity
3 of the perforations 30 may vary with cross-sectional dimensions and service
4 conditions. For example, the perforations 30 may be smaller and/or more
5 numerous.

6 To manufacture the unitary structural member 10 of the present
7 invention, particularly types of embodiments that include perforations 30, a
8 number of methods are disclosed and described below. The description below,
9 however, is not intended to limit the particular scope of manufacturing methods
10 contemplated for the unitary structural member 10.

11 FIG. 8 is an analytical taxonomy of preferred types of processes for
12 manufacturing the metal unitary structural member 10 of the present invention.
13 As described in the legend of FIG. 8, those manufacturing processes with a
14 capacity to produce the metal unitary structural member 10 are highlighted in gray
15 and with a black dot.

16 There are two preferred general categories of manufacturing
17 processes for producing the metal unitary structural member 10 of the invention.
18 The metal unitary structural member 10 can be manufactured indirectly using
19 various types of investment (ceramic mold) casting. The invention can also be
20 made directly or indirectly using additive metal forming technologies. All
21 preferred methods of manufacturing the metal unitary structural member 10,
22 however, typically require three-dimensional data obtained from digital solid

1 models of the invention. These production processes are, therefore, what are
 2 generally termed computer-aided manufacturing (CAM) processes. A summary of
 3 preferred fundamental CAM processes for making the metal unitary structural
 4 member 10 is presented in FIG. 9. Those fundamental manufacturing processes
 5 with the capacity to produce member 10 with internal features are highlighted with
 6 a black square in the column to the far right in to FIG. 9.

7 The metal unitary structural member 10 having perforated web
 8 portions 12 can be investment cast in most alloys from additively or subtractively
 9 formed expendable patterns. Additively formed patterns are made from digital
 10 data using commercially-available computer numerically controlled (CNC) layer-
 11 based solid freeform fabrication technologies and materials suitable for
 12 combustion or melting. Subtractively-formed patterns are made from digital data
 13 using commercially-available multi-axis CNC milling machines or routers.
 14 Depending on the required size of the metal unitary structural member 10, it will
 15 often be necessary to subdivide the member into segments that can fit within the
 16 build chamber of a solid freeform fabrication device. These segments can be
 17 made to self-register with the correct orientation and then simply glued together as
 18 shown in FIG. 2. Patterns made using subtractive methods will have to be
 19 subdivided to accommodate otherwise inaccessible internal features (i.e. internal
 20 perforated webs will necessarily be discreet CNC milling operations). The
 21 resulting self-registering subtractively formed pattern components are then
 22 assembled into a complete pattern.

1 In order to make the metal unitary structural member 10 having
2 perforated web portions 12, it is preferred first to create a digital representation of
3 it in a parametric solid modeling program that can accommodate and facilitate the
4 generation of complex geometry. Examples of such software include
5 Pro/Engineer® by Parametric Technology Corporation, Unigraphics Solutions®
6 by EDS, and Catia® by Dessault Systemes. It is also preferred to use such
7 software because it can accommodate the digital assembly of subcomponents
8 and/or the subdivision of large components into segments small enough to fit in
9 the build chamber of a particular additive manufacturing process.

10 Once a particular metal unitary structural member 10 has been
11 digitally modeled, the model is then either directly or indirectly (via data exchange
12 in a neutral format such as IGES) imported into finite element analysis software
13 and evaluated per the anticipated structural service conditions. Specific material
14 properties will then be applied to the model prior to analysis, and this analysis will
15 further inform and refine the optimization of the component in terms of its
16 strength-to-weight ratio. In other words, material usage in terms of wall thickness,
17 web 30 thickness, and the size and configuration of perforations 30 will be
18 digitally optimized relative to the required strength (plus a safety factor). In most
19 cases, it is likely that a variety of the perforations 30 for the web portions 12 will
20 be digitally modeled in advance of analysis, along with a varying quantity of the
21 web portions. This will make it possible for the analytical results of several
22 potentially optimal configurations to be compared and assessed. It is most likely

1 that the various web portion 12 and perforation 30 configurations would exist in
2 the same digital model as either parametric variables or sets of geometric features
3 that can be turned on and/or off prior to the exportation of data. Digital structural
4 analysis will also highlight areas of critical stress where there is insufficient
5 material as well as situations where there is excess material that might be removed
6 from the model if it is not required for manufacturing reasons.

7 In addition to structural optimization analysis, if the metal unitary
8 structural member 10 is to be manufactured indirectly using an investment casting
9 process, data from its digital model will usually be exported to a manufacturing
10 analysis program that will assist in evaluating castability. Casting analysis
11 programs (e.g. MAGMASoft®) are used to predict the flow of molten metal and
12 the solidification process and are therefore are able to anticipate likely casting
13 defects. In some cases, the extent to which the metal unitary structural member 10
14 can be optimized will be slightly constrained by the need to accommodate casting
15 requirements such as directional solidification (ferrous alloys) and thorough
16 distribution of molten metal in the ceramic mold.

17 Once the results of structural and manufacturing analyses have been
18 incorporated into the computer model for the metal unitary structural member 10,
19 and once the member has been segmented or subdivided as necessary to
20 accommodate a particular pattern manufacturing technology, the data defining
21 surface geometry is exported in an appropriate format, typically in a neutral file
22 format. This data is then imported into computer-aided manufacturing (CAM)

1 software. If pattern components are to be made using a subtractive process, the
 2 computer code that will direct the automatic carving of these pattern components
 3 out of blocks of material using a CNC milling machine will be generated using a
 4 CAM program such as MasterCAM® or SurfCAM®. If pattern components are
 5 to be manufactured using an additive material forming process, then the geometric
 6 data will be imported into the proprietary CAM software provided by
 7 manufacturers of commercial solid freeform fabrication devices. All CAM
 8 programs for additive material forming, however, provide the means to orient the
 9 component as desired and then subdivide it using a slicing algorithm into very thin
 10 horizontal layers of a specified thickness. The layer thickness selected will
 11 determine the dimensional accuracy of complex surfaces. Thinner layers result in
 12 superior resolution and accuracy, whereas thicker layers will result in a faster
 13 build rate.

14 The metal unitary structural member 10 having perforated web
 15 portions 12 can be investment cast from expendable patterns made using a variety
 16 of commercially-available layer-based solid freeform fabrication (SFF)
 17 technologies. In general, SFF technologies that utilize powdered material are the
 18 most suitable for making expendable patterns for investment casting the unitary
 19 structural members. This is because these SFF technologies use the surrounding
 20 bed of powdered material to temporarily support the pattern during the build
 21 process, and because powder supporting the freeform tubular pattern's interior can
 22 be easily removed with gravity and air flow. SFF technologies that require and

1 generate insoluble support structures for overhanging features are less suited to the
2 manufacture of the metal unitary structural member 10 because of the difficulty
3 and necessity of removing these internal temporary support structures prior to
4 investment casting.

5 Three-dimensional printing (3DP) and selective laser sintering (SLS)
6 are the two major powder-based SFF technologies. Three-dimensional printing
7 technology uses a standard ink-jet print head to deposit a water-based liquid binder
8 onto a starch (cellulose) powder. This binder is deposited in an area
9 corresponding to a thin horizontal cross-section of the model. The build chamber
10 is then lowered per the specified layer thickness, and a roller spreads another layer
11 of powder before the next section is printed. This process is repeated layer by
12 layer until the pattern is finished, at which time it is then removed from the build
13 chamber, dried and infiltrated with wax or resin. 3D printed patterns can be easily
14 sanded and coated as required for investment casting, and they combust without
15 leaving significant residual ash in the ceramic mold. One type of commercial 3DP
16 devices that can produce combustible patterns investment casting is manufactured
17 by Z Corporation and marketed as concept modelers because it has a relatively fast
18 build rate and slightly less precision than many other commercially available SFF
19 technologies. For many applications of the metal unitary structural member 10,
20 however, the accuracy of the process is suitable or can be circumvented by CNC
21 machining connective interfaces between members.

Selective laser sintering technology was developed at the University of Texas and commercialized by DTM Corporation in Austin. EOS Gbmh in Germany also developed SLS and both companies manufacture their own range of machines. SLS is very versatile and can process a variety of materials including polymer powders, sand, and metal powders. SLS uses laser heat to raise the temperature of powdered polymers (or the binder that coats grains of sand or metal) to the point where individual grains fuse together. As with 3DP, SLS parts are supported by surrounding powder while being built layer by layer. Both DTM Corporation and EOS Gbmh produce materials designed for use in foundries. SLS produces very dimensionally accurate expendable patterns.

Exceptionally accurate wax patterns for casting very small metal unitary structural members 10 having perforated web portions 12 can be made using the ModelMaker™ liquid-to-solid inkjet printers manufactured by Sanders Prototype, Inc. While this technology automatically generates temporary support structures for overhanging features, these supports are built out of a different material that can be dissolved with a solvent that will not damage the pattern per se. In other words, the support structures for the perforated web portions 12 can be removed even though they are physically inaccessible.

Fused deposition modeling (FDM) is a SFF technology that uses a computer controlled extrusion head to incrementally deposit layers of melted thermoplastic materials. FDM machines are manufactured by Stratasys® Inc. and the company produces a wax material designed for use in making expendable

1 patterns. Like the other thermoplastic materials available for FDM, this foundry
2 wax solidifies immediately after being deposited. Water soluble temporary
3 support materials for FDM have been developed for use with ABS, but liquid-
4 based support structure removal is not currently available for the foundry wax
5 used with FDM. This means that FDM is significantly less useful for making
6 patterns for casting the metal unitary structural member 10 having perforated web
7 portions 12.

8 While very accurate, stereolithography is another SFF technology
9 that generates temporary internal support structures that are problematic for
10 making the metal unitary structural member 10 having perforated web portions 12.
11 Stereolithography machines are manufactured by 3D Systems and their build
12 chamber is a vat of ultraviolet-sensitive liquid polymer. The application of laser
13 light solidifies the liquid polymer layer by layer from the bottom up until a
14 component is completely built. In order to use this technology to create
15 expendable patterns, proprietary QuickCast™ software currently must be used.
16 This software generates a honeycomb structure within the wall thickness of a
17 pattern, and this internal configuration enables the pattern to collapse inward
18 during combustion without applying destructive forces to the ceramic mold.
19 QuickCast™ patterns have been used successfully commercially, but they can be
20 problematic, and extensive foundry experience is generally required to assure a
21 reasonable likelihood of success. The difficulty of using stereolithography to
22 create expendable patterns combined with the likely impossibility of being able to

1 remove temporary internal support structures render the technology a distinctly
2 less useful means of manufacturing patterns for making the metal unitary
3 structural member 10 having perforated web portions 12.

4 Multi-jet modeling (MJM) is a SFF technology developed by 3D
5 Systems to quickly produce concept models and to build expendable patterns out
6 of a wax material. MJM is commercially marketed as the Thermojet™ solid
7 object printer. This process, however, also generates temporary support structures
8 for overhanging features, and these have to be manually removed (i.e. water-based
9 solutions or solvents are not available to dissolve inaccessible temporary
10 supports), rendering MJM distinctly less useful for creating patterns for making
11 the metal unitary structural member 10 having perforated web portions 12.

12 Investment casting is the most common and precise of the
13 expendable ceramic mold metal casting processes, and the term is often used to
14 generically refer to all expendable ceramic mold techniques. Other casting
15 processes that use ceramic molds can also be used to indirectly manufacture the
16 metal unitary structural member 10, and they are similar enough to investment
17 casting to be covered by the process description below. These other processes
18 include those utilizing a flask into which a ceramic slurry is poured, and those that
19 support a ceramic mold with compacted sand, namely the Replicast® process, and
20 lost foam metal casting.

21 An investment casting mold is created by investing an expendable
22 pattern with a refractory shell by successively dipping it ceramic slurry, coating it

1 ceramic mold processes have been used to cast much longer components, in some
2 cases up to twelve feet. In these cases, a hybrid process using compacted sand to
3 support a ceramic mold has typically been used. The size constraint in most
4 foundries is the autoclave used to combust the invested pattern. The investment
5 casting process is described in detail in FIG. 10 and is also illustrated below in the
6 description showing a prototypical example of indirectly manufacturing the metal
7 unitary structural member 10.

8 An illustrative example of an investment casting method for
9 manufacturing the metal unitary structural member 10 having perforated web
10 portions 12 will now be described according to one type of method to manufacture
11 the present invention. The production process for manufacturing the metal unitary
12 structural member 12 using investment casting is summarized in FIG. 11.
13 Expendable patterns for this prototype were three-dimensionally printed using data
14 exported from parametric computer models of the invention. These patterns were
15 then invested with a ceramic shell and combusted. The resulting ceramic mold
16 was used to cast this prototype in 356 aluminum, and these castings were then
17 heated treated to maximize their strength.

18 A portion of the metal unitary structural member 10 having
19 perforated web portions 12 was designed using Pro/Engineer® parametric solid
20 modeling software. The overall curvilinear length of this prototype is
21 approximately two feet, and the circular area in which a cross-section of the
22 member 10 can be inscribed ranges from approximately 5 inches in diameter to 3.5

1 inches in diameter, although the model can be easily parametrically modified so
 2 that these cross-sectional dimensions can vary greatly per service conditions and
 3 optimization analysis. The spline or curved trajectory of this particular member
 4 10 lies in a plane, thereby making this tube symmetrical. The web portions 12,
 5 their perforations 30, the outer surface 14 (corrugated), and the openings at the
 6 connective structure 24 can also be parametrically modified in size and shape in
 7 order to facilitate shape and structural optimization. The connective structure 24
 8 between what would otherwise be two 68-inch long members was incorporated
 9 into this prototype in order to evaluate and verify one possible design of such a
 10 connection. Images of the pattern component computer models are shown in
 11 FIGs. 12 and 13, and screen captures of digitally assembled patterns are shown in
 12 FIG. 14.

13 As is shown in FIG. 15, expendable patterns for the prototype metal
 14 unitary structural member 10 were three-dimensionally printed on a Z Corporation
 15 Z402 3D Printer. Two of these pattern components are shown in their “green”
 16 state after powder removal in FIG. 16. Each pattern component was infiltrated
 17 with resin in order to obtain sufficient strength for handling and assembly in the
 18 foundry, as well as to facilitate further finishing of the external surfaces for
 19 aesthetic reasons.

20 The patterns of a component per se are referred to as the part
 21 patterns in ceramic mold casting processes. Complete patterns ready for
 22 investment feature gates, runners and other elements that have been attached to the

1 these openings at the ends of the members 10 is also optimal in terms of investing
2 the pattern with slurry (which has to drain well from cavities after dipping), air
3 drying each coat, and creating structural bridges between cavity molds and the
4 outer ceramic shell. The perforation of internal webs creates exceptional ceramic
5 mold strength and integrity. In other words, the optimizing features of the metal
6 unitary structural members also significantly enable their indirect manufacture
7 using investment casting.

8 The castings for the prototype metal unitary structural member 10
9 having perforated web portions 12 are shown with some of their gating cut off in
10 FIG. 25. Initial removal of the gating was done with a band saw, and this
11 operation left about ¼ inch of each gate on the surface of the castings. Most of
12 this was removed using belt grinding machines, and the results of this process are
13 shown in FIG. 26. Each of the gate locations was then carefully blended using
14 hand held grinding devices as shown in FIG. 27. Evidence of surface grinds
15 quickly and completely disappeared after the castings were sand blasted, although
16 this was not done until after the two parts had been welded together.

17 In order to be able to present the connection in this prototype in both
18 a welded and a non-welded state, the decision was made to weld two-thirds of the
19 circumference of the joint. The components for the prototype metal unitary
20 structural member having perforated web portions are shown being welded
21 together in FIG. __. The slight discoloration of the welded joint visible in FIG. 29
22 (left) is the result of an immersion heat treatment.

1 Prior to the specified heat treatments, the prototype metal unitary
2 structural member 10 was sand blasted to provide consistent surface texture and
3 ensure that the gates and weld had been thoroughly blended with adjacent surfaces
4 (i.e. it is difficult to verify surface accuracy because of the markings created
5 during grinding). Photographs of the welded castings during the sand blasting
6 process are shown in FIG. 30.

7 Two heat treatments processes that are typically specified for
8 structural aluminum components and are normally used in conjunction with each
9 other were applied to the prototype metal unitary structural member 10. The first
10 heat treatment process is the T-4 heat treatment, and it involves immersing
11 castings for 24 hours in liquid (mostly water) that is heated to a temperature 100°F
12 less than the melting point of the alloy (in this case, therefore, 1175°F). This
13 process permits much more controlled solidification of a casting and results in a
14 higher degree of homogenization among the various alloying ingredients. When a
15 casting is removed from a T-4 heat treatment, it is immediately quenched to
16 'freeze' the metal in this improved state. The second heat treatment is air-based
17 rather than water-based, and is known as the T-6 process. This process involves
18 placing a casting in a furnace and heating it to a temperature between 300°F and
19 350°F for a few hours to artificially harden the metal and increase its strength.
20 The duration of a T-6 heat treatment is usually a few hours, but the precise time is
21 determined by the foundry based on experience and the part's geometry.

100-1930-12301
"02672007"

1 Prior to the castings being welded together, they were inspected
2 visually and using both dye-penetrant and radiographic techniques. Visual and
3 dye-penetrant inspection showed no surface defects, and x-rays indicated that the
4 castings were sound throughout. In fact, both castings easily met the standards of
5 ASTM E155 for structural aluminum castings and what is referred to as '3T
6 sensitivity', which is a standard required of high performance castings for the
7 aerospace industry.

8 Radiographs of castings that are to be evaluated per ASTM and other
9 standards include a series of slides with three tiny but different sized holes in
10 them. (These slides may be purchased from the American Society for Testing and
11 Materials (ASTM).) Each slide corresponds to a specific casting wall thickness,
12 and because most castings have more than one wall thickness, several different
13 slides are usually required for a given radiograph. The tiny holes in each of these
14 slides are sized relative to a specific casting wall thickness, and they serve to
15 control the interpretation or 'reading' of a radiograph. If these holes are visible on
16 a radiograph, then that means that voids or inclusions in the casting corresponding
17 to the sizes of these holes would also be visible in the radiograph. Because each
18 of these tiny holes has a different diameter or, more loosely, 'thickness', standards
19 are specified based on the number of holes that are visible. The term 'thickness' is
20 generally abbreviated with the letter 'T', and readability standards are therefore
21 specified as '1-T', '2-T' and '3-T'. Most aluminum castings are required to meet
22 2-T standards, but many small commercial castings are only required to meet 1-T

1 standards. The aerospace industry, NASA, and other businesses making products
2 with stringent performance specifications typically demand 3-T certification. Two
3 radiographs of the metal unitary structural member having perforated web portions
4 are shown in FIGs. 31 A and B. Both of these castings met '3-T' standards.

5 As described above, in addition to indirect investment casting
6 methods, the present invention contemplates manufacturing the metal unitary
7 structural members 10 using direct methods. The metal unitary structural member
8 10 having perforated web portions 12 can be directly manufactured using various
9 laser and metal powder based freeform fabrication technologies. These processes
10 use lasers (or sometimes heat from another energy source) to bond metal powders
11 that are delivered through nozzles to the heat source. These methods can be
12 described as layer-based multi-axis CNC metal deposition or welding. Examples
13 of these processes are discussed below.

14 The metal unitary structural member 10 having perforated web
15 portions 12 can also be semi-directly manufactured using other metal powder-
16 based solid freeform fabrication (SFF) technologies, namely three-dimensional
17 printing (3DP) and selective laser sintering (SLS).

18 These processes can be considered semi-direct methods of
19 manufacturing metal components because they initially result in skeletal or porous
20 (approximately sixty-percent dense) products that then must be infiltrated with
21 molten metal (typically bronze) to create fully dense parts. At present, these
22 methods, like investment casting, result in material properties that may not be

1 sufficient for some service conditions. However, the companies that manufacture
2 SLS machines that can process metal powders, DTM Corporation and EOS GmbH,
3 are developing improved materials and processing techniques in an effort to
4 minimize this issue. Extrudehone's ProMetal® Division, which manufactures
5 three-dimensional printing machines specifically for processing metal powders, is
6 also developing improved materials and processes. It is possible that the metal
7 products of SLS and 3DP machines will eventually be able to better capture the
8 strength to weight ratio advantages of the metal unitary structural members 10.
9 Process diagrams for the indirect additive manufacture of metal components using
10 SLS and 3DP are shown in FIG. 32.

11 Selective laser sintering processes use a carbon dioxide laser to
12 sinter and thereby bond powdered materials. A thin layer of powdered material is
13 spread over a build piston that is lowered incrementally after each layer has been
14 sintered. Each sintered layer represents a horizontal section through the part.
15 Layer thickness controls the accuracy or resolution of the part being built. SLS
16 was first developed for application using powdered polymers, which are readily
17 bonded by the application of heat, but, from a material standpoint, the process is
18 more flexible than most solid freeform fabrication technologies because polymeric
19 binders can be easily added or applied to ceramic or metal powders. Varieties of
20 metal powders that have been coated with polymeric binders are commercially
21 available. SLS machines have build chambers that are approximately 15" by 13"
22 by 18" high.

1 After an entire part has been sintered, it is removed from the powder
2 and considered to be in a green state. The polymer remaining in green parts is
3 then burned off in a reducing atmosphere furnace, leaving a stainless steel skeleton
4 that is about sixty percent dense. This initial heat treatment also further sinters the
5 metal. Bronze is infiltrated into the steel skeleton in a second heat treatment,
6 creating a part that is fully dense. Metal parts semi-directly manufactured using
7 SLS have a strength and hardness superior to aluminum. Their modulus of
8 elasticity and coefficient of thermal expansion are similar to steel, and they can be
9 easily machined, welded and finished.

10 A three dimensional printing (3DP) process was invented at MIT
11 and is licensed to several companies. Each of these businesses is developing
12 different material technologies. The ProMetal® Division of Extrude Hone
13 Corporation in Pennsylvania has commercialized the use of metal powders to
14 make tools and components using 3DP. They manufacture a line of solid freeform
15 fabrication devices commercially named ProMetal® machines. These machines
16 have build volumes ranging from 12" by 12" by 10" high to 20" by 36" by 12"
17 high.

18 ProMetal® machines print a polymeric binder onto layers of
19 powdered stainless steel or tool steel using an ink jet printhead that deposits
20 320,000 droplets per second. As with SLS, and as indicated in FIG. 32, this
21 produces a green part in a bed of loose powder. The remaining polymeric binder
22 is then burned out in a furnace in a process that also lightly sinters the part. A

1 second heat treatment is used to infiltrate the steel skeleton with molten bronze or
2 a copper alloy, creating a fully dense part. Completed parts are approximately
3 sixty percent steel and forty percent bronze (or copper) and these steel/bronze
4 parts have sufficient material properties for some structural applications. Three
5 dimensionally printed metal parts can be machined, welded and finished as if they
6 were stainless steel parts made using other manufacturing processes.

7 Embodiments of the metal unitary structural member 10 having
8 perforated web portions 12 may be directly manufactured using solid freeform
9 fabrication technologies that are generally referred to as layer-based metal
10 deposition processes. Various names have been given to specific direct metal
11 freeform manufacturing technologies by those organizations developing or
12 commercializing these processes, and these include laser-engineered net shaping
13 (LENSTM), direct metal deposition (DMDTM), and laser additive manufacturing
14 (LAMTM). All of these processes use nozzles to deliver metal powder or wire to a
15 focused heat source, usually a laser but sometimes another energy source. The
16 nozzles and heat source collectively comprise what is known as the deposition
17 head, and these assemblies are typically manipulated in at least three axes using
18 computer numerical control (CNC) software. In a process very similar to welding,
19 the heat source melts the powder or wire resulting in a small but controllable
20 molten pool that quickly solidifies and bonds with the layer below as the
21 deposition head follows a predetermined computer numerically controlled layer-
22 specific path. As with the majority of solid freeform fabrication technologies,

10019201
T.O.E.F.T. "O.E.B.T.O.T."

1 each layer corresponds to a thin horizontal cross-section of the component.
2 Because direct metal deposition processes are essentially multi-axis CNC
3 automated robotically manipulated welding processes, they (like welding)
4 generally result in fully dense products with material properties that match or
5 exceed those found in wrought products generated by deformation processes such
6 as rolling, extrusion or forging. As a result, direct metal deposition processes have
7 the potential to better capture the optimized strength to weight ratio and stiffness
8 advantages of the unitary metal structural members 10.

9 While the material properties created by most laser and metal
10 powder based freeform fabrication technologies are excellent, the machines and
11 software currently available have significant limitations in terms of their capacity
12 to manufacture the invention. It is anticipated that many of these limitations will
13 be reduced or eliminated as these technologies are further developed, and that they
14 will, therefore, eventually have a greater capacity to manufacture the invention.

15 A current limitation of most laser and metal powder based freeform
16 fabrication technologies is their inability to build features that overhang at an
17 angle greater than approximately 30 degrees off of vertical orientation. The path
18 planning and build software available with most direct metal processes does not
19 automatically generate temporary support structures, and the only way to remove
20 physically inaccessible temporary supports would be to build them using an alloy
21 with a significantly lower melting temperature than the alloy(s) with which the
22 component per se is made, and then melt the support structures in a heat treatment

10021930-121301

1 process. In many instances, the better solution to the present geometric limitations
2 of direct metal deposition processes will be to develop six-axis manipulation that
3 can accurately and predictably deposit metal from any orientation, and to
4 supplement this capacity with path planning software that can successfully
5 sequence the deposition of metal so that unbuilt portions of features do not
6 become inaccessible during the build process. Process is currently being made on
7 developing such solutions to the current geometric limitations of laser and metal
8 powder based direct manufacturing processes.

9 Commercially available machines manufactured by Optomec, Inc.
10 (LENS™) and Precision Optical Manufacturing (POM), for example, are capable
11 of manufacturing some smaller scale applications of the metal unitary structural
12 members. It is contemplated that further development and application of gantry-
13 based delivery mechanisms and robotically manipulated multi-axis deposition of
14 metal at an equal rate from the top, sides, or bottom of a component, in machines
15 such as fully-functioning direct metal deposition machines currently being
16 developed by Lockheed Martin Aeronautics Company, may be used to
17 manufacture the metal unitary structural member 10 having perforated web
18 portions 12 using direct metal manufacturing processes.

19 A number of embodiments of the invention, the metal unitary
20 structural member 10 have thus been shown and described, having at least the
21 several advantages described above. A number of methods have also been shown

1 and described for producing various types of embodiments of the metal unitary
2 structural member 10.

3 While various embodiments of the present invention have been
4 shown and described, it should be understood that other modifications,
5 substitutions, and alternatives are apparent to one of ordinary skill in the art. Such
6 modifications, substitutions and alternatives can be made without departing from
7 the spirit and scope of the invention, which should be determined from the
8 appended claims.

9 Various features of the invention are set forth in the appended
10 claims.

10021930 12101